**IRON-NICKEL(-COBALT) METAL IN LUNAR ROCKS REVISITED.** A. Wittmann[1] and R. L. Korotev[1]. Department of Earth & Planetary Sciences, Washington University in St. Louis, One Brookings Drive, St. Louis, MO 63130, wittmann@levee.wustl.edu.

**Introduction:** Iron-nickel metal particles have long been used as proxies for meteoritic contamination or to support the pristine character of lunar rocks [1-4]. These alloys also yielded cooling rates and related depths of equilibration in the lunar crust [5,6].

In Shişr 161, a lunar feldspathic regolith breccia, low bulk-rock siderophile-trace-element concentrations of 88 ppm Ni and 2.6 ppb Ir indicate minor meteoritic contamination [7]. Our survey of metal and sulfide particles in Shişr 161 [8], and their petrologic contexts probes into constraints for their origins. This study aims to complement whole rock siderophile element abundances [7] and what these abundances can tell about projectile types or the lunar crust's indigenous siderophile component.

**Samples and Methods:** About 60 metal and 30 sulfide particles were analyzed with the electron microprobe in a 550 mm$^2$ thin section and a 90 mm$^2$ thick section of Shişr 161. Two of these particles are 60 and 40 µm size nuggets. The rest are ~5–20 µm size particles associated with troilite and silicate melt components.

**Results:** Host materials for the metal and sulfide particles comprise impact melt glasses and –vitrophyres, crystallized spherules, crystallized impact melts that have average grain sizes <0.03 mm, and 0.03–0.3 mm. A sub-class of crystallized impact melt clasts exhibits cumulate textures and average grain sizes of 0.05–0.35 mm.

Troilite is the most common sulfide phase in Shişr 161. It is frequently intergrown with ~1–5 µm metal particles. Concentrations of P are typically <0.03 wt% and Ni concentrations range from <0.06 wt% to a few wt%. Three pentlandite particles have 33.0–42.3 wt% Fe, 33.6–33.8 wt% S, 22.6–28.2 wt% Ni and 1.11–5.19 wt% Co, comparable to lunar and terrestrial pentlandites [9,10].

Most metal particles have typical sizes <10 µm and are associated with troilite. These alloys are typically hosted in the mesostasis melt of vitrophyres. In the crystallized melt particles, they frequently occur in-between olivine and plagioclase or as inclusions in plagioclase, less frequently next to pyroxene. Only two metal particles are associated with chromian spinel. However, these particles contain 56.4 and 13.9 wt% Ni, which is inconsistent with reduction of spinel [11,12].

Ni concentrations in FeNi metal particles are 0.14–58.2 wt%, and Co concentrations are 0.11–3.58 wt% (Fig. 1). Only one metal particle, a 60 µm nugget in the regolith breccia matrix, is a polyphase intergrowth of tetrataenite (53.4 wt% Ni, 0.14 wt% Co) and kamacite (6.8 wt% Ni, 0.8 wt% Co) that has a composition typical for equilibrated L-chondrites [13,14].

Metal particles in spherules and vitrophyres have Ni concentrations <30 wt%. Most of these particles plot within the typical range, or in extensions of the field for "meteoritic iron" [1] (Fig. 1), or within the compositional range of metal particles in Apollo 17 basalts [2]. Metal particles in a very fine-grained melt clast plot similar to alloys in granulite breccia 79215 [22], with an affinity towards kamacite in LL-chondrites [13,14].

Most metal particles in melt clasts with proto-poikilitic textures follow the "cosmic"-chondritic Co/Ni ratio of 0.05 [21]. Only one cumulate melt clast out of eight contains metal particles with Ni abundances <35 wt%. Their Co/Ni ratios tend to follow the "cosmic trend", albeit variations occur among metal particle populations within the same clasts. For example, one cumulate clast hosts taenite particles with Ni concentrations of 37.7 and 42.9 wt%, and Co of 2.1 and 3.1 wt%, respectively.

Concentrations of P are ≤0.03 wt% in all metal particles except those in four clasts – two spherules, one glassy melt and one proto-poikilitic melt clast – where they reached up to 0.5 wt% P. Coincidentally, the Ni and Co abundances of these particles plot within, or in extensions of the "meteoritic field" [1].

The clast that hosts metal particles with the highest P concentrations is a crystallized spherule. It contains an assemblage of troilite, FeNi metal, and an FeNi phosphide with up to 9.5 wt% P, 15.4 wt% Ni, 0.3 wt% Co, and 70 wt% Fe.

**Discussion:** Pentlandite forms in the Fe-Ni-S system at ambient pressures at temperatures <610 °C [23], if sufficient Ni is present [24]. Compositions of three pentlandite particles in Shişr 161 are similar to pentlandite in a Luna 24 ferrobasalt [9]. Few other pentlandite particles have been reported from lunar samples and involved relatively exotic petrogeneses [25-27]. In Shişr 161, pentlandite occurs as inclusions in plagioclase and at the grain boundaries of olivine, pyroxene and plagioclase in two crystallized melt particles. Taenite particles in these clasts have ~chondritic Co/Ni.

Very high Ni and Co concentrations in metal particles within lunar igneous rocks are not uncommon. Single- and two-phase metal particles occur in Apollo 15 soil samples [5]. The single phase metal particles with high Ni abundances contain between 45.0–60.0 wt% Ni and 0.25–4.4 wt% Co. FeNi metal particles with high Ni concentrations (up to 56 wt%) and high Co concentrations (up to 9 wt%) also sometimes occur in lunar basalts, mostly as inclusions in early crystallized olivine [11,12,28].

Thirteen metal particles with Ni >35 wt% and Co >1 wt% are enclosed in plagioclase. However, high Ni metal particles in pristine lunar rocks were linked to olivine-rich rocks with high MgO/FeO [4]. Because the host clasts for most of the high Ni metal particles in Shişr 161 are crystallized impact melt particles that are formed by igneous processing in large melt sheets [29], two sources for these Ni-Co-rich particles seem probable. One is projectile material that became mixed and diluted in a large volume of impact melted lunar crust. The second are olivine-rich rocks in the lower lunar crust, similar to dunite 72415/7, in which Ni-Co rich metal particles co-crystallized with olivine. The affinity of Ni/Co to a chondrite-like ratio in dunite 72415/7 may not be too surprising in light of recent studies that found elevated highly siderophile element concentrations in mantle rocks from the Earth [30], the Moon [30], Mars [31], and Vesta [32], which were related to a late veneer of meteoritic material during the last stages of initial crystallization of these lithospheres.

**References:** [1] Goldstein J. I & Yakowitz H. (1971) *Proc. LSC 2nd*, 177-191. [2] Smith J. V. & Steele I. M. (1976) *Am. Min. 61*, 1059-1116. [3] Warren P. H. & Wasson J. T. (1979) *Proc. LPSC 10th*, 583-610. [4] Ryder G. et al. (1980) *Proc. LPSC 11th*, 471-479. [5] Axon H. J. & Goldstein J. I. (1973) *EPSL 18*, 173-180. [6] Gooley R. et al. (1974) *GCA 38*, 1329-1339. [7] Korotev R. L. (2012) *MAPS 47*, 1365-1402. [8] Korotev R. L. (2013) *LPSC LXIV*, abstract # 1028. [9] Nazarov M. A. et al. (1980) *LPSC XI*, 800-802. [10] Anthony J. W. et al. (1990) *Handbook of Mineralogy*, MSA, Chantilly, VA., 588 pp. [11] Reid A. M. et al. (1970) *EPSL 9*, 1-5. [12] Brett R. et al. (1971) *Proc. LSC 2nd*, 301-317. [13] Kallemeyn G. W. et al. (1989) *GCA 53*, 2747-2767. [14] Rubin A. E. (1990) *GCA 54*, 1217-1232. [15] Dymek R. F. et al. (1975) *Proc. LSC 6th*, 301-341. [16] Jolliff B. L. et al. (2003) *GCA* 67, 4857-4879. [17] Prinz M. et al. (1973) *Science* 179, 74-76. [18] Warren P. H. & Wasson J. T. (1979) *Proc. LPSC 10th*, 583-610. [19] Warner R. D. et al. (1980) *Proc. Conf. Lunar Highlands Crust*, 377-394. [20] Nehru C. E. et al. (1978) *Proc. LPSC 9th*, 773-788. [21] Warren P. H. (1993) *Am. Min. 78*, 360-376. [22] Bickel C. E. et al. (1976) *Proc. LSC 7th*, 1793-1819. [23] Kullerud G. (1963) *Can. Min. 7*, 353-366. [24] Ma et al. (1998) *J. Phase Equilibria 19*, 299-309. [25] Ramdohr P. (1972) *EPSL 15*, 113-115. [26] Carter J. L. et al. (1975) *Proc. LSC 6th*, 719-728. [27] Kuehner S. M. et al. (2005) *LPSC XXXVI*, abstract #1228. [28] Anand M. et al. (2003), *MAPS 38*, 485-499. [29] Wittmann A. et al. (2013) *LPSC LXIV*, abstract #2061. [30] Day J. M. D. et al. (2007) *Science 315*, 217-219. [31] Brandon A. D. et al. (2012) *GCA 76*, 206-235. [32] Day J. M. D. et al. (2012) *Nature Geosciences 5*, 614-617.

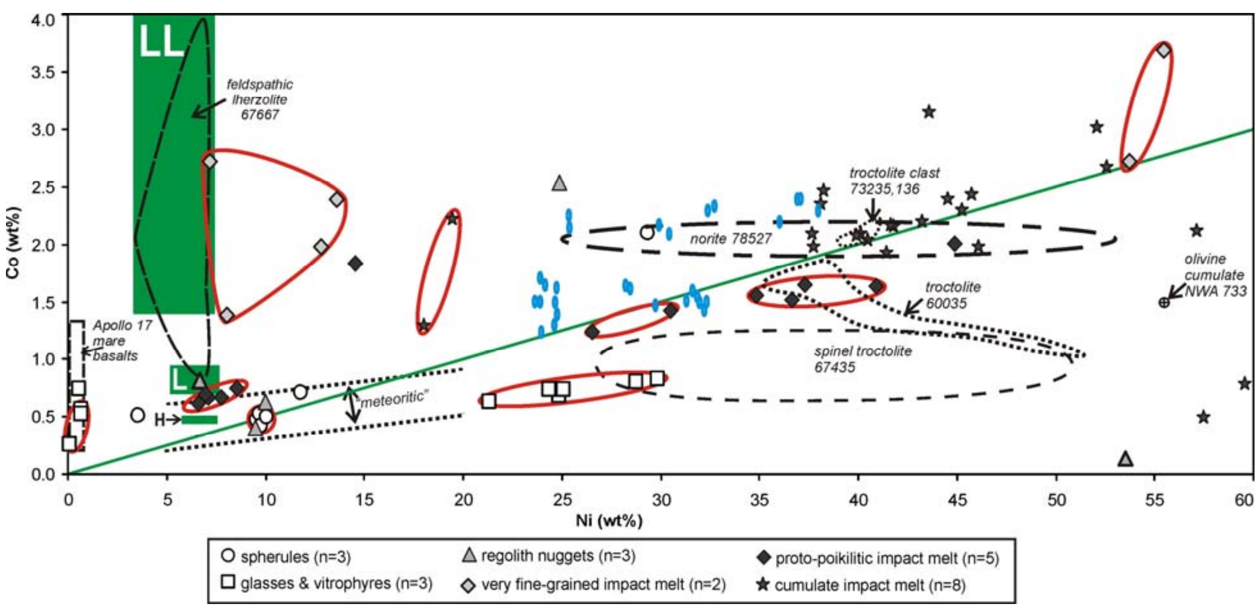


*Fig. 1 Nickel versus Cobalt in metal particles in clasts of Shişr 161.*
*Fields for compositional ranges of kamacite in equilibrated H, L and LL chondrites after [13,14]; Apollo 17 basalts field after [2]; "meteoritic field" after [1]; green line marks Co/Ni of 0.05, the "cosmic"/chondritic trend. Blue dots mark compositions of metal particles in dunite 72415/7 after [4,15], dot for olivine cumulate in NWA 733 after [16]; fields for spinel troctolite 67435 after [17], "feldspathic lherzolite" (an olivine gabbro norite) 67667 and troctolite clast in 73235 after [18], troctolite clast 60035 after [19], norite 78527 after [20]. Note that according to [21] 72415/7 score a pristinity class of 9 and are most likely pristine, 67435 scores 8.1, and 67667 scores 7.4 - both are confidently pristine, 60035 scores 6.1 and is pristine with caution, 73235 scores 4.4, and 78527 scores 4, which suggests both are doubtful pristine. All Shişr 161 data normalized to 100 wt%.*